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Shipyard Aluminum/Steel Welded Transition Joints IVB-4

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ABSTRACT

Aluminum to steel explosion welded transition joints are used in shipbuilding to attach aluminum superstructures to steel hulls. This paper summarizes long term studies to determine causes of separations and describes actions to prevent separations.

The aluminum/steel transition joints are manufactured by the explosion welding process and tested in accordance with MIL-J-24445. Traditional transition joints consist of alloyed aluminum bonded (by the explosion weld) to mild steel with an interlayer of low alloy aluminum. In 1989, production began using an improved transition joint product with the addition of a titanium interlayer between the steel and the low alloy aluminum. Laboratory testing showed the improved product had greater strength and temperature resistance. However, when this product was put into production, disbonding occurred at an alarming rate. As a result, it was discovered that bond notch toughness is a critical property even though it was not required to be measured by MIL-J-24445. To improve the notch toughness while preserving earlier beneficial improvements, a ductile copper nickel (CUNI) interlayer was added between the steel and the titanium.

This paper describes the study results and the development of the latest generation of aluminum steel structural transition.

DEFINITIONS

ABS- American Bureau of Shipping; refers to their steel plate classifications

AL- Aluminum metal

ASTM- American Society for Testing Materials

CUNI- Copper Nickel alloy metal

DT- Dynamic Tear, ASTM standard E-604; measurement of energy absorption to break a notched specimen considerably larger than an IZOD specimen

EXW- Explosion Weld; the process of fusing two metals together at a bond surface by using the force of an explosion

IZOD- ASTM standard E-23-82; measurement of energy absorption to break a specimen similar to Charpy vee notch except that the pendulum strikes a cantilevered specimen

MIL- Military Specification (U.S. Government)

SCAST- Structurally Critical Aluminum Steel Transition

TI- Titanium metal

UT- Ultrasonic Testing

BACKGROUND

Aluminum cannot be arc welded directly to steel because of metallurgical incompatibility. Aluminum to steel welds can be produced using cold welding processes, such as explosion welding (EXW). Conventional arc welding processes then can be used to attach the EXW transition to respective compatible metal components. This combination provides a crevice free, fully welded joint between aluminum and steel. This is a significant advantage over mechanical fastening by riveting or bolting.

The aluminum to steel transition joints typically are welded to a steel coaming about five inches above the topmost steel deck. The EXW transition joint supports the bulkhead plating, vertical stiffeners and framing. See figure 1 for a typical design. Early installations used 35 mm (1-3/8 in) thick transition joints. Recent designs use 19 mm (3/4 in) thick transition joints.

In the mid-1980's, some shipboard bonded joints separated as a result of normal operations in high sea state conditions. These disbonds resulted in closely focused attention on all bond joints. The separations were puzzling because these EXW transition joints were

designed to be the "strong link" in the structural chain (stronger than the aluminum plating welded to the joint).

Ships under construction were closely examined. For about a year, locations of disbond repairs were monitored to analyze why the disbonds were occurring. Most disbonds were associated with butt welds in the transition strips. Butt welding causes local disbonds, typically less than 10 mm (3/8") due to weld heat and stress. Also, 92% of the disbonds were in narrow strips which have less thermal mass to absorb the welding heat input, resulting in higher temperatures-at the bond during fillet welding. All known disbonded locations have always been repaired before any ship left the shipyard. Disbonding in service is rarely reported, so apparently disbond in fleet service is unusual.

In 1990, 38 mm (1.5 in) thick improved trimetallic (AL-TI-STEEL) with higher strength ABS grade DH 36 steel base layer transition was placed into production after extensive laboratory research. The research confirmed high tensile strength and temperature resistance. In production, four of eight weldments developed disbonds of up to 70% of their length. Some disbonding occurred several hours or days after welding was completed. The disbonded areas continued to grow for several days after inception, eventually growing to several feet long. That 38 mm thick, DH 36 based trimetallic was immediately pulled from production and ordinary bimetallic was substituted. No 38 mm trimetallic was ever actually installed on board any ship. The disbonding was attributed to a combination of low notch toughness, large weld related stresses (due to full penetration welding and high yield strength steel), and restraint provided by the large weldments. A 19 mm (3/4") thick improved trimetallic with an ordinary strength steel base layer transition remains in production with no known disbond to date.

Transition Joint Manufacture

Aluminum to steel bonded transition joints are manufactured in accordance with the requirements of MIL-J-24445. The only process currently used for manufacture of shipboard transition joints in the USA is explosion welding. A roll bonded product is being evaluated, but results were not available in time to be included in this paper. Reference (1) provides a thorough description of the technology and of the development of aluminum to steel transition joints for shipboard applications. References (2) and (3) provide a summary of the process. Figure 2 depicts the basic explosion bonding process.

In the early explosion bonding development work discussed in Reference (1), it was observed that a direct explosion weld between aluminum 5000 series alloys and steel exhibited low strength and poor toughness. The deficiency was corrected by insertion of an interlayer of unalloyed aluminum, type 1100, between the marine grade 5456 aluminum and the steel. The original 35 mm (1-3/8 in) thick transition joints consist of 6.3 mm (1/4 in) thick 5456 aluminum alloy bonded to an interlayer of 9.5 mm (./375 in) thick 1100 aluminum and a base of 19 mm (0.75 in) steel. Later, 19 mm (3/4 in) thick transition joints were made using 3.2 mm (0.125 in) thick 5456 or 5086-aluminum alloy bonded to a 6.4 mm (0.25 in) thick interlayer of 1100 aluminum and a base of 9.5 mm (0.375 in) steel. Although these products are actually comprised of three alloy layers, they are commonly referred to as "bimetallic" transition joints. Besides 1100 aluminum, other interlayers may be employed to obtain various bond properties.

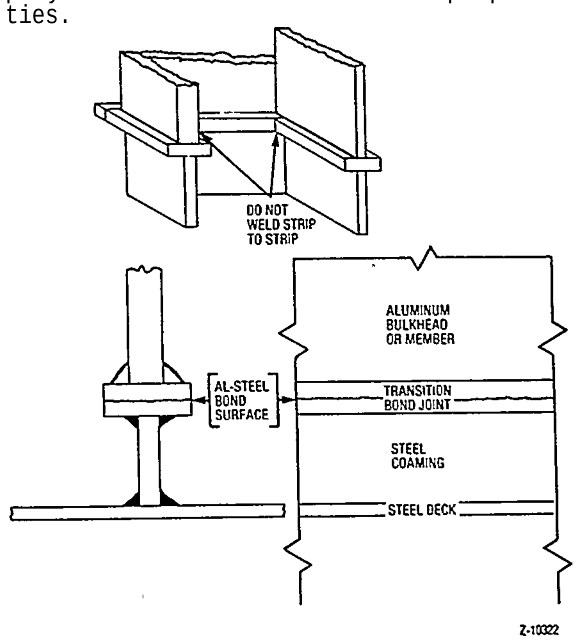


Figure 1. Typical Joint Design

Transition Joint Quality Testing

Aluminum to steel welded transition joints are quality tested in accordance with the requirements of MIL-J-24445. This specification requires 100% ultrasonic testing (UT) of every plate by straight beam transducer to detect areas of non-bond. Although ultrasonic testing will reliably detect non-bond, it can not detect areas of low bond strength.

In addition to UT, one plate from every lot, or 1 in 10, whichever is more frequent is mechanically tested. Test specimens must be cut from two diagonally opposite corners of the selected plates. Ram tensile tests and a side bend test are required. Neither test will evaluate notch toughness. Since EXW transition joints rarely pass side bend

test, MIL-J-24445 provides bond shear strength and chisel testing as a substitute for side bend. The chisel test is a qualitative but unreliable indicator of notch toughness. Before tensile testing, some samples are heat treated 15 minutes at 315 C (600 F) to simulate the "as welded" condition. Specification requirements are: 55.2 MPa (8,000 PSI) minimum shear strength; 75.8 (11,000 PSI) minimum tensile strength; and no bond failure in either the side bend test (if used) or the chisel test (if substituted).

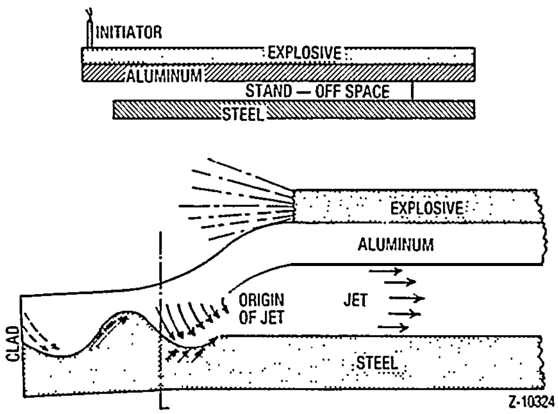


Figure 2. Parallel arrangement for explosion cladding and subsequent collision between the prime and backer metals that leads to jetting and formation of wavy bond zone.

Bond Separations Study

Reference (3) discusses in detail the bulk of the research. The following paragraphs provide a summary of reference (3).

(1) BOND TEMPERATURE- Thermocouples were located at the bond surface under fillets to measure the actual bond temperatures occurring during various weld processes. These tests showed that shipyard welding practices were not overheating the bond joints above the 315 C (600 F) allowable temperature.

(2) FILLET SIZE- Oversize aluminum fillets out to the edge of the strip did not cause degradation in bond strength.

(3) BOND MATERIAL CHANGES OVER TIME- Bimetallic bond tensile strength has not appreciably changed with time, although there are variations between manufacturers. Independent testing and vendor review showed that all manufacturers were testing in compliance with MIL-J-24445.

(4) DESIGN WIDTH- The standard recommendation is to provide transition strip widths four times the thickness of the aluminum member (see figure 1). Statistical analysis in reference (3) showed this standard is marginally acceptable. Wider transition joint strips could be used to lower stress, but with undesirable weight increase.

(5) RESTRAINT & WELD SHRINKAGE STRESSES- Restraint and thermally induced stresses are significant, but don't normally, in and of themselves, cause disbonding. However, when the DH 36 based trimetallic went into production, restraint provided by a 25.4 mm (1 in) thick HY-80 steel web combined with thermal stresses due to full penetration welds was sufficient to initiate disbonding.

The studies to date clearly show that structural transition reliability can best be improved by improving the provisions of Mil-J-24445. The 38 mm (1.5 in) DH 36 trimetallic bond was tested well beyond existing provisions, yet was found unsuitable for structurally critical ship production applications. The DH 36 trimetallic's strength was nearly double the minimum and it was much more temperature resistant. It even passed the side bend test (usually). Every plate was tested, although MIL-J-24445 only requires samples from one plate in ten. However, MIL-J-24445 does not require notch toughness testing and the DH 36 trimetallic had slightly lower notch toughness than the standard bimetallic product. MIL-J-24445 is now undergoing revision and many changes are a direct result of the recommendations reference (3) and the lessons learned from the DH 36 trimetallic.

SCAST

SCAST is an acronym for Structurally Critical Aluminum Steel Transition. The Navy expressed a need for a highly reliable, high strength aluminum steel transition joint with a higher strength steel substrate for a structurally critical location. The product was intended to join the CG 47 class sheer strake to the forward side of the superstructure. While the DH 36 trimetallic product discussed earlier met the target of improving tensile strength and thermal degradation resistance, initial production clearly showed that notch toughness was important.

Improved notch toughness became an additional goal for development. The initial fabrications showed that weld shrinkage stresses were sufficient to initiate a disbond, probably at a locally weak area. Once the disbond began, it easily progressed through the brittle TI/steel bond until the shrinkage stresses were relieved. Thus the DH 36 trimetallic was not suitable as a Structurally Critical Aluminum Steel Transition.

The principal manufacturer of the trimetallic product produced an experimental quadmetallic product to solve the notch toughness problem. The goal was to develop an aluminum steel transition joint with at least twice the strength, improved heat resistance, and twice the

notch toughness of the bimetallic product. The principal difference between their SCAST and the trimetallic is the addition of a copper nickel (CUNI) layer between the higher strength steel and the titanium. The exact formulation and the special EXW processing are regarded as proprietary by the manufacturer.

As MIL-J-24445 did not address a need for bond notch toughness, three tests were used to quantify the relative notch toughness of different material compositions. The goal was to develop a SCAST product that would have at least twice the notch toughness of conventional bimetallic products, regardless of which test method was used. The final SCAST formulation meets this goal. The simplest test consisted of cutting a notch into both ends of the welded tensile samples. The notch geometry was the same as that for a dynamic tear specimen, ASTM E-604. Also, notched specimens were prepared in accordance with ASTM E-23-82 with notches placed at bimetallic AL/steel bond and quadmetallic steel/CUNI, CUNI/TI and TI/AL bond surfaces. Finally, dynamic tear (DT) specimens were prepared with notches at the CUNI/TI bond, which was found to be the lower energy bond by earlier IZOD tests.

The notched tensile test showed that the strength advantage of the trimetallic and initial quadmetallic products relative to the standard bimetallic product did not remain after notching. In the notched tensile test, bimetallic bond strength dropped from about 82.7 MPa (12 KSI) for unnotched specimens to about 41.4 MPa (6 KSI) for specimens notched at the bond. Quadmetallit tensile bond strength dropped from about 172 MPa (25 KSI) to about 41.4 MPa (6 KSI) for the early product. After these tests, the quadmetallic material formulation was slightly changed to further improve notch toughness, resulting in SCAST-2 which had a notched tensile strength of 103 MPa (15 KSI). After more testing, the EXN manufacturing process was again modified to further improve notch toughness, resulting in SCAST-3. As the desired notched tensile stress for SCAST should be at least twice that of bimetallic, it appears that the third generation quadmetallic meets this goal.

The IZOD testing showed that the energy absorption of quadmetallics was vastly better than bimetallic. Bimetallic samples absorbed, on the average, about 12.2 Nm (9 foot-pounds). Improved quadmetallic SCAST samples, on the average, absorbed about 59.6 Nm (44 foot-pounds). The later test results may not be valid because SCAST IZOD specimens would not fail at the bond. Even with the notch at the bond, there was no disbonding at all. Instead, the specimens plastically bent in the 1100 aluminum. Thus, what was really measured was the energy absorbed in plastic deformation of the aluminum, not the energy absorbed in disbonding. Numerically, the quadmetallit SCAST surpassed the goal of absorbing twice the energy of bimetallic bonds.

The dynamic tear (DT) testing also showed that the energy absorption of the improved quadmetallic SCAST was significantly better than bimetallic. Bimetallic DT samples absorbed, on the average, about 65.1 Nm (48 foot-pounds). Improved quadmetallic DT samples, on the average, absorbed about 228 Nm (168 foot-pounds). The improved quadmetallic SCAST-3 surpassed the goal of twice as much energy absorption as bimetallic.. As disbonding occurred in both types of product specimens, this test is believed to be a more representative measure of notch toughness of the bonds. Mil-J-24445 is currently being revised to incorporate dynamic tear testing. There will be further product testing before numerical values can be incorporated into the revision.

Cost Considerations

Improved SCAST transition joint material costs about 10% more than conventional bimetallic material in plate form. The increased material cost for the SCAST material prompted a study of ways to reduce the cost. This cost in-

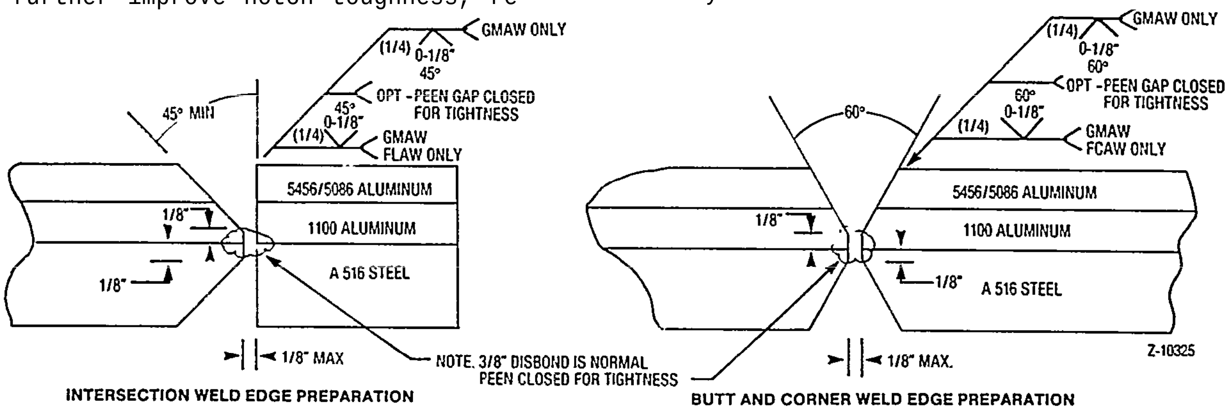


Figure ***3. Recommended butt joints in transition strips***

crease is offset by improved safety margin (reliability) and by using narrower strips due to the higher tensile strength of the trimetallic. The improved resistance to thermal degradation of SCAST and trimetallic materials permits high speed, low cost plasma cutting versus the high cost mechanical cutting used for heat sensitive conventional bimetallic strips. That improved thermal degradation resistance also permits production savings when high deposition rate spray GMAW and FCAW processes are used to install the strips (versus lower heat pulsed GMAW). Overall, the SCAST product can actually cost less than the standard bimetallic.

CONCLUSIONS

An (ABS DH 36) steel-titanium-aluminum explosion welded transition joint was found to be highly susceptible to disbonding in a production environment. Laboratory testing showed the bond was more resistant to thermal degradation and had much higher strength that bimetallic joints. Examination of disbonded weldments showed disbond initiation and growth in the titanium to steel bond surface. A similar but thinner trimetallic with ordinary strength steel has not experienced any disbonds. It was concluded that, because strength and surface hardness are related, the DH 36 trimetallic may have a more brittle bond. Research then began to develop a product preserving the-advantages of the DH 36 trimetallic (high bond strength, improved temperature resistance) but with improved notch toughness. The research successfully produced Structurally Critical Aluminum Steel Transition (SCAST) joints. Compared to conventional bimetallic bond joints, SCAST improves the bond strenath from 82.7 MPa (12 KSI) to 172 MPa (25 KSI), improves temperature resistance from 315 C (600 F) to 515 C (950 F) and improves dynamic tear notch toughness from 65.1 Nm (48 Ft-Lbs) to 228 Nm (168 Ft-Lbs).

In conclusion, SCAST transition joints greatly improve the reliability while offering potentially lower overall costs.

RECOMMENDATIONS

MIL-J-24445

Naval Sea Systems Command (NAVSEA) is currently in the process of revising MIL-J-24445 to add a new grade of material (SCAST) which would require notch toughness testing, higher bond strength, and higher heat soak before testing. Other changes planned will require chisel testing for all grade products and a revised sampling plan with testing near the EXW initiation point and the farthest corner.

Design

A conscientious designer will want to use the best materials within cost constraints. The conventional bimetallic joint developed in the 1960's demonstrates lower strength, is much more sensitive to heat, and now is much more "brittle" (low notch toughness) than the newest SCAST products. Clearly, SCAST is a better material by every engineering measurement. If the designer is free to choose minimum widths, and if high speed plasma cutting processes is an acceptable alternative, SCAST designs will actually be a lower cost alternative to bimetallic. Even if the width cannot be reduced and plasma cut edges are not acceptable, the increased reliability may justify the slight increase in purchase cost for saw cut strips.

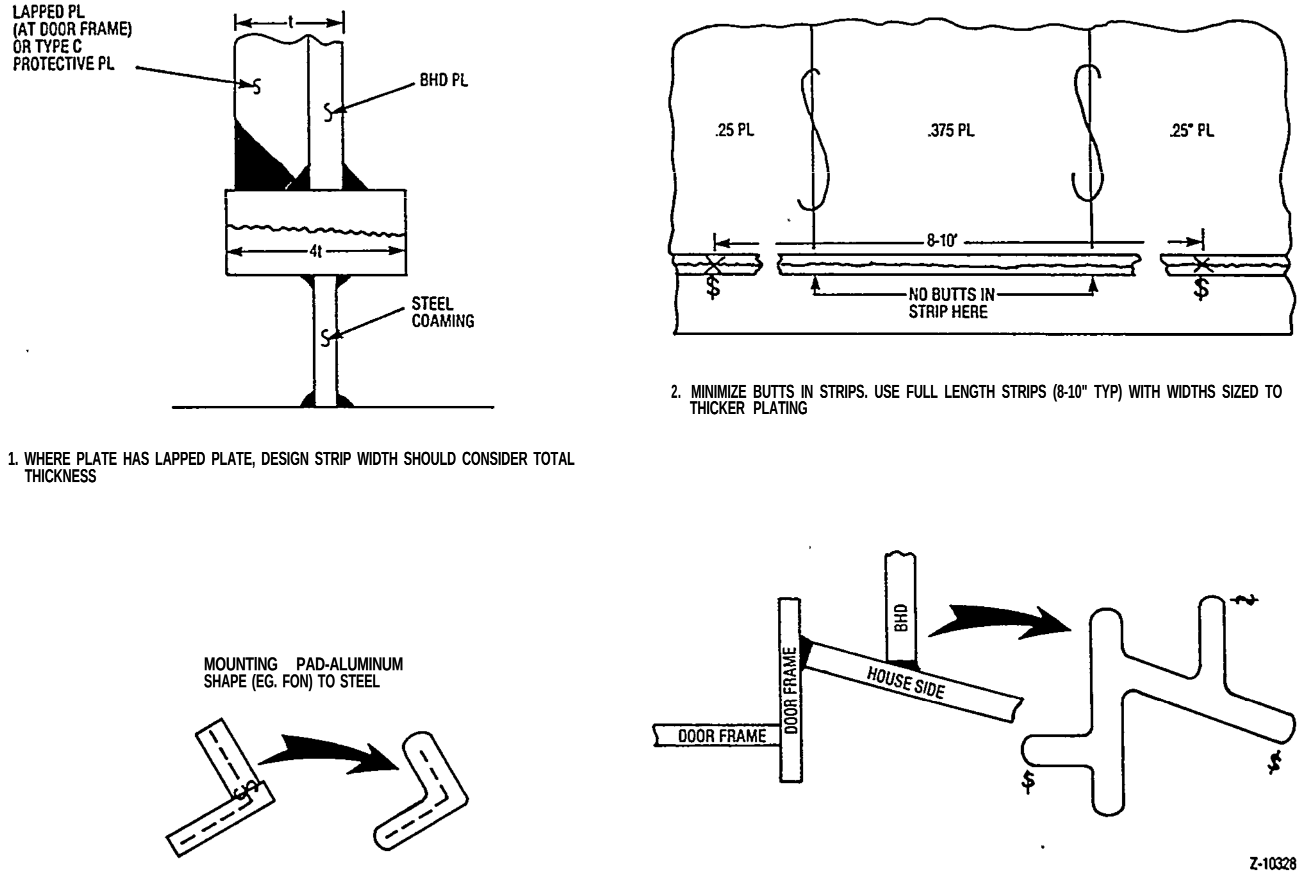
There are some design suggestions from reference (3) which should be repeated here. The standard rule of thumb is to use strip widths of 4 times aluminum plate thickness. However, statistical knowledge of actual strengths of welded transition joint and structural plating should be considered in establishing design guidelines. If a 1% disbond rate is considered acceptable, the recommendation based on data reported in reference (3) would be to provide bimetallic strip widths of 4.24 times the thickness of the aluminum plating. Minimum widths of the SCAST material would be on the order of 3 to 1. These recommendations may be modified to take into account the width of weld fillets and needed reliability at strip butts where notches may exist.

The designer should always specify a partial penetration butt design (as shown in figure 3) and should give preference to designs which minimize the number and proximity of butt welds. See figure 4 for some ideas.

Production

The peak bond joint temperature of bimetallic transition joints is limited to 315 C (600 F) by the manufacturers. This limits the processes which can be used for welding. It also requires cool down time between weld passes to reduce interpass. SCAST is not nearly as temperature sensitive. Tensile tests show no significant degradation at significantly higher temperatures. Future research will determine the acceptable peak and interpass temperatures based on tensile and dynamic tear testing after exposure to various high temperatures.

When plasma cutting, the highest feasible travel speed should be used and the composite plate should be submerged. Periodic tensile and bend testing of plasma cut strips would be a wise precaution. Such samples should be cut near the explosion weld initiation point, if that is known.



1. WHERE PLATE HAS LAPPED PLATE, DESIGN STRIP WIDTH SHOULD CONSIDER TOTAL THICKNESS

2. MINIMIZE BUTTS IN STRIPS. USE FULL LENGTH STRIPS (8-10" TYP) WITH WIDTHS SIZED TO THICKER PLATING

3. SIMPLIFY BY PLASMA CUTTING PADS FROM PLATE

4. SIMPLIFY BY CUTTING COMPLEX INTERSECTIONS WITH PLASMA

***Figure* 7. Some designer recommendations**

SUMMARY

Some aluminum to steel bimetallic transition joints were disbonding in ships under construction and, to a lesser extent, in the fleet. This was unusual because the strips were designed to be stronger than the aluminum plating attached. Studies were made to determine the causes and recommend corrective measures. Several possible causes were found, some eliminated, and preventative measures instituted. The most significant improvements were in design and materials. During the course of the study, a new trimetallic (aluminum-titanium-steel) transition joint was certified to MIL-J-24445 and introduced into production. The trimetallic design provides higher strength and higher resistance to heat degradation during installation welding while offering potentially lower overall costs. However, the notch sensitivity of the trimetallic titanium to steel bond lead to further material improvements through the development of a quadmetallit (aluminum-titanium-copper nickel-steel) Structurally Critical Aluminum Steel Transition (SCAST). Compared to conventional bimetallic aluminum steel transition, SCAST has twice the tensile strength, twice the notched tensile strength, four times the dynamic tear notch toughness, and extends heat degradation resistance from 315 C (600 F) to nearly 538 C (1000 F). MIL-J-24445 is being revised to incorporate lessons learned during the study reported in this paper.

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